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Decisions about the axes of disoriented shapes

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Subjects were timed as they made decisions about the location of an asterisk placed to the left, right, top, or bottom of disoriented shapes, and their reaction times were plotted as a function of the angular departure of the shapes from the upright. In Experiment 1, the shapes were letters, and the functions suggested that the subjects generally mentally rotated some internal representation of each letter to the upright in order to decide whether the asterisk was to the left or the right, regardless of whether the letters were vertically symmetrical (*A, T, U, V*), horizontally symmetrical (*B, C, D, E*), or asymmetrical (*F, G, R, L*). For decisions about top and bottom, mental rotation rarely occurred, although there was some evidence for it in the case of horizontally symmetrical letters. Experiment 2 showed that mental rotation was not involved when subjects made one response if the asterisk was to the left or right, and another if it was at the top or bottom. In Experiment 3, the shapes were relatively unfamiliar architectural symbols, and in this case mental rotation was most strongly induced by those decisions requiring mirror-image discrimination, that is, left-right decisions for vertically symmetrical shapes and top-bottom decisions for horizontally symmetrical ones. Taken overall, the results suggest that there are two task ingredients that may induce mental rotation: One is the labeling of the left and right sides of a disoriented shape, and the other is the discrimination of mirror images.

People can usually recognize visually presented shapes or objects regardless of how they are oriented in space. There are some exceptions; for instance, Rock (1973) has pointed out that faces are peculiarly difficult to recognize when upside down, and that cursive handwriting is very difficult to read when upside down. Usually, however, we are well able to recognize objects in orientations that do not match the orientations of our retinas. From an ecological point of view, this is not surprising, since gravity acts as only a loose constraint on our own orientations and on the orientations of detachable objects. We should be poorly adapted indeed if we could not recognize an automobile parked on a slope or a book lying on the floor.

One way in which an observer might recognize a disoriented shape is by extracting a description that is orientation-free. Rock (1973) argued, however, that the assignment of orientation, which he regarded as a cognitive act, was critical to recognition. "In general," he wrote, "a disoriented figure will not be recognized unless the observer achieves a correct assignment of directions (by one means or another), or unless the new orientation does not alter phenomenal shape very much, as in a left-right reflection" (p. 127). By "assignment of directions," Rock meant the identification of top, bottom, and sides. For instance, a tilted square may be recognized as a square if its top-bottom axis is seen as running parallel to two of its sides, but as a diamond if the top-bottom axis is seen as running between opposite corners. Rock attached greater importance to the top-bottom axis than to the left-right one, noting that recognition is little affected if left and right sides are interchanged, as in a mirror reflection.

Following the work of Shepard and Metzler (1971), Rock (1973) also suggested that the assignment of directions was accomplished by mental rotation. Shepard and Metzler showed that when observers were required to decide whether pairs of line drawings represented the same or different objects, their reaction times to make "same" decisions increased linearly with the angle between the objects. They took this to mean that the observers "mentally rotated" one object into concordance with the other. Rock (1973, p. 76) suggested that "precisely this kind of mental process is involved in the perception of retinally disoriented figures." That is, the observer assigns directions to a disoriented figure by mentally rotating it to the upright.

But there is a paradox here. Unless the observer knows at least one of the axes of the figure *prior to* mental rotation, how can he or she mentally rotate it to the upright? Logically it would be sufficient to know where, for instance, the top of the figure is, and then to use this as a basis for mental rotation; however, if the observer already knows which is the top, there seems little point in carrying out a mental rotation to discover this. It is conceivable that mental rotation is a matter of trial and error, in which the observer mentally tries out different angular orientations until recognition occurs. But in the case of highly familiar shapes, at least, the empirical evidence seems to weigh against this possibility.

This evidence stems from the work of Cooper and Shepard (1973), who timed observers as they decided whether alphanumeric characters in varying angular orien-

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tations were normal or backward (i.e., mirror reversed). Decision times increased sharply with the angular departure of the characters from the upright. Cooper and Shepard (1973) interpreted this to mean that the subjects mentally rotated some internal representation of each character to the upright before making the decision—an interpretation consistent with the subjects' own introspections. It is logical to suppose that the subjects must have known the identity and orientations of the characters before mental rotation, for otherwise they could not have known how far to rotate them.

Other evidence confirms that mental rotation is not involved when observers are required simply to name disoriented alphanumeric characters (Corballis, Zbrodoff, Shetzer, & Butler, 1978), or to categorize them as letters or digits (Corballis & Nagourney, 1978; White, 1980). Similarly, mental rotation does not seem to occur when subjects identify disoriented symbols that resemble letters but are relatively unfamiliar (Eley, 1982). This is not to say that recognition is entirely orientation free in these cases. Recognition time may show some dependence on angular orientation (Jolicoeur & Landau, 1984), but the function is much flatter than the "mental-rotation" function reported by Cooper and Shepard (1973). There is one revealing exception, however. If observers are required to identify the lowercase letters *b*, *d*, *p*, and *q*, then identification time does show the sharp dependence on angular orientation indicative of mental rotation, regardless of whether the discrimination required is between left-right mirror images (*b* vs. *d*, *p* vs. *q*) or between up-down mirror images (*b* vs. *p*, *d* vs. *q*) (Corballis & McLaren, 1984). The letters *b*, *d*, *p*, and *q* are exceptional in that their identification requires implicit mirror-image discrimination.

Mirror-image discrimination appears, in fact, to have been a common ingredient in all reported studies of mental rotation, or at least in all those using the basic paradigm developed by Cooper and Shepard (1973). For instance, mental rotation functions have been reported in the discrimination of left from right hands depicted in varying orientations (Cooper & Shepard, 1975), in the discrimination of mirror-image letter-like symbols (Eley, 1982), and in the discrimination of mirror-image random polygons (Cooper & Podgorny, 1976). Cooper and Shepard (1973) argued that the mirror-image relation was critical because mirror images cannot be distinguished on the basis of their features. For example, both a forward and a backward *R* might be said to comprise the same featural elements, namely, two straight lines and a curved line, interconnected in the same way. Consequently, according to Cooper and Shepard (1973), the problem of deciding whether a shape is normal or mirror reversed can only be solved in holistic fashion, by rotating it, mentally or physically, to its normal upright orientation and comparing it with an internally generated representation of the shape.

To some degree, this account might be said to beg the question, since mirror images are featurally indistinguishable only if one discounts the parity, or left-right orientation, of the features themselves. Even so, it is difficult, if not impossible, to devise a description of a shape that is independent of angular orientation and at the same time dependent on its parity. The function of mental rotation, then, might well be to establish "which way round" a shape is, perhaps with reference to the observer's own left and right sides (Corballis, 1982; Corballis & Beale, 1983).

In the present study, subjects were shown shapes in varying angular orientations and were timed as they made decisions concerning the axes of those shapes. These decisions had to do with the location of an asterisk that could be placed to the top, bottom, left, or right of each shape relative to its own internal coordinates. The primary question was whether or not these various decisions involved prior mental rotation of the shape to its normal upright orientation. Our aim, therefore, was to determine what the subjects know about the axes of a shape prior to mental rotation, and what aspects require mental rotation before they are known.

The shapes themselves could be vertically symmetrical (e.g., the letters *A*, *T*, *U*, and *V*), horizontally symmetrical (e.g., *B*, *C*, *D*, and *E*), or asymmetrical (e.g., *F*, *G*, *L*, and *R*). The symmetry of the shape is relevant in that it determines whether or not there are featural elements distinguishing top and bottom or left and right. Let us now consider various hypotheses as to which of the various decisions might induce mental rotation.

First, if Rock (1973) is correct, then all decisions should require mental rotation. That is, if a shape cannot be recognized until its axes are specified, and if specification of axes requires mental rotation, then all decisions about which is the left, right, top, or bottom of the shape should require mental rotation. We have already seen, however, that recognition of familiar shapes, such as letters, does not seem to require mental rotation, although it remains conceivable that identification of their axes does. It is also possible that identification of less familiar shapes might require mental rotation.

Second, if Cooper and Shepard (1973) are correct, then those decisions requiring mirror-image discrimination should induce mental rotation. The only decisions requiring mirror-image discrimination in the present study are, first, whether an asterisk is to the left or right of a vertically symmetrical shape (such as *A*), and second, whether an asterisk is to the top or bottom of a horizontally symmetrical shape (such as *E*). Neither type of decision can be based on distinctive features, so the subject might be forced to mentally rotate the shapes to the upright in order to refer the axes of the shapes directly to the axes of space. All other decisions—top-bottom decisions about vertically symmetrical shapes, left-right decisions about horizontally symmetrical shapes, both types of decisions about asymmetrical shapes—can be based on distinctive features marking the axes of the shapes, and thus, according to Cooper and Shepard's (1973) account, do not require mental rotation.

Third, it is possible that mental rotation has to do specifically with the left and right sides of a shape. Left and right are egocentrically defined: they can be understood only with reference to the left and right sides of our own bodies (see Corballis & Beale, 1983). In deciding whether a shape is normal or backward, for example, as in the Cooper-Shepard paradigm, the subject might be forced to solve the problem by referring the sides of the shape to his or her own left or right sides. If this is the dominant factor, then we might expect subjects in our experiments to have to resort to mental rotation only when required to decide between left and right placements of the asterisk.

Our main criterion for deciding whether or not mental rotation was the dominant strategy under any given condition was the shape of the function relating decision time to angular orientation. Previous studies involving decisions about singly presented stimuli suggest that mental rotation gives rise to a function that is symmetrical about, and peaks sharply at, the 180° orientation, and that represents a mental-rotation rate of about 400 deg per sec (dps), with rates for individuals ranging from about 164–800 dps (e.g., Cooper & Shepard, 1973). The function often exhibits a flattening at orientations close to the upright, probably because subjects do not always mentally rotate the stimuli the full angular distance to the upright (Hock & Tromley, 1978). As evidence for mental rotation, then, we sought a function with these properties.

A possible objection is that the rate of mental rotation may vary with experimental conditions. For instance, the rate estimated by Shepard and Metzler (1971) in their experiment was only about 60 dps, which is markedly slower than the rate of about 400 dps typically estimated from experiments using the Cooper-Shepard paradigm. There is evidence, however, that when subjects are required to match simultaneously presented pairs of differently oriented stimuli, as in the Shepard-Metzler paradigm, they mentally rotate in piecemeal fashion, comparing the stimuli part by part (Just & Carpenter, 1976; Shepard & Cooper, 1982). This paradigm, therefore, probably underestimates the rate of holistic mental rotation. In the present study, we take the view, articulated and documented by Shepard and Cooper (1982), that holistic mental rotation of singly presented stimuli is largely independent of stimulus or task properties.

We recognize, however, that mental rotation may not be an all-or-none strategy, and therefore, that there can be no absolute criterion for specifying the presence or absence of mental rotation. Functions resembling those reported by Cooper and Shepard (1973) are taken as evidence that mental rotation is at least the dominant strategy, whereas functions that are more or less flat are taken as evidence that mental rotation is seldom induced. As we shall see, however, some functions fall between these extremes; our interpretation is that mental rotation is an intermittent strategy rather than that there are variations in mental-rotation rate.

EXPERIMENT 1

In this experiment, the stimuli were letters, and the subjects were required simply to call out whether the asterisk was to the "left," "right," "top," or "bottom" of each letter.

Method

Subjects. Eight undergraduates volunteered as subjects. Four were men and 4 were women; their ages ranged from 17 to 40 years. Two of the women and 1 man were left-handed in terms of the hand used for writing and drawing.

Apparatus and Stimuli. The stimuli were "Eurostile" capital letters 6.9 mm high from Letraset Sheet No. 2993, impressed onto the center of white cards measuring 15 cm wide × 10 cm high. Four letters (*A*, *T*, *U*, *V*) were vertically symmetrical, four (*F*, *G*, *R*, *L*) were asymmetrical, and four (*B*, *C*, *D*, *E*) were horizontally symmetrical, except that there was a slight horizontal asymmetry in the letter *B* which is discernible in Figure 1. Each of these 12 letters was presented in six angular orientations: 0°, 60°, 120°, 180°, 240°, and 300° clockwise from the normal upright. In addition, each letter had an asterisk marker, the largest from Letraset Sheet No. S7543, placed about 2 mm to the left, right, top, or bottom of each letter, relative to its own coordinates (examples are shown in Figure 1). Each letter was presented four times in each orientation, once with each marker position. The 288 stimuli were presented twice in random order to each subject in a Gerbrands four-field tachistoscope, so that each subject received a total of 576 trials. The viewing distance was 1 m, so that each letter subtended a visual angle of 0.4° lengthwise at the subject's eyes.

Procedure. On a given trial, the subject was shown a central fixation dot for 1 sec, followed by a blank warning flash for 100 msec, a return of the fixation dot for 500 msec, then presentation of the stimulus for 2 sec. Presentation of the letter coincided with the onset of an electronic timer connected to a voice key, which stopped the timer when the subject spoke. Subjects were instructed to say whether the asterisk was to the "left," "right," "top," or "bottom" of the letter with respect to the letter's own coordinates. Emphasis was placed on accuracy rather than speed, but the subjects were also told that their responses were being timed. If the subject made an error, the card was extracted and presented later in the series, so that a correct response was obtained for every stimulus. Twenty practice trials were given at the start of the session.

Results and Discussion

The subjects made a total of 57 errors, an error rate of 1.24%. These were too few for systematic analysis, but it was noticeable that the errors for left and right placements (1.95%) exceeded those for top and bottom ones

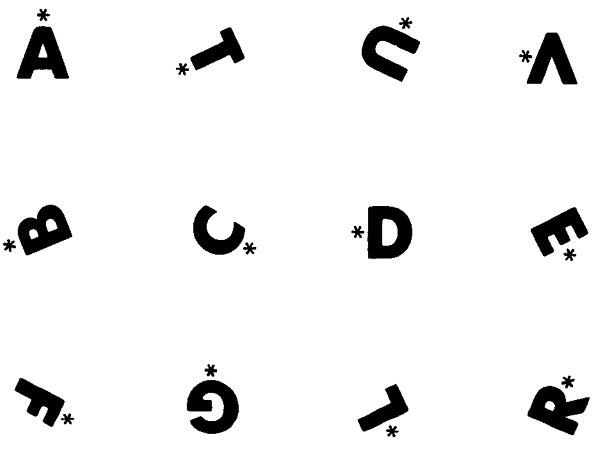

Figure 1. Examples of the stimuli used in Experiment 1.

(0.52%). This difference was significant [$t(7) = 4.09$, $p < .01$].

The reaction times (RTs) for correct responses were subjected to an ANOVA in which the factors were axis of symmetry of the letter (vertical, horizontal, or none), angular orientation of the letter, axis of the marker (left-right or top-bottom), position of the marker (left vs. right, top vs. bottom), letter, and gender of subject.

There were significant main effects of angular orientation [$F(5,30) = 27.65, p < .01$], axis of marker [$F(1,6) = 27.34$, $p < .01$], and letter [$F(9,54) = 6.67$, $p < .01$]. Of more relevance was a significant interaction between axis of marker and angular orientation [$F(5,30) = 13.69, p < .001$]. As shown in Figure 2, the peaked orientation function characteristic of mental rotation was clearly evident only when the subjects made "left" and "right" judgments, regardless of the axis of symmetry of the letters. There was some suggestion of peakedness with top-bottom decisions, especially in the case of horizontally symmetrical letters, but it seems clear that mental rotation cannot have been more than an intermittent strategy in this case.

Had mental rotation been restricted to those decisions requiring mirror-image discrimination, as Cooper and Shepard (1973) suggested, then we should have obtained a triple interaction between axis of symmetry, axis of marker, and angular orientation, but in fact this interaction did not approach significance [$F(10,60) = 1.19$]. Figure 2 shows that mirror-image discrimination may have played some role in top-bottom decisions, however, in view of the more peaked functions for horizontally than for vertically symmetrical or asymmetrical letters, but there is no evidence for a comparable effect in left-right decisions.

To explore more closely how well these functions did, in fact, fit the hypothesis of mental rotation, the slopes of the best-fitting linear functions relating RT to angular departure from the upright were estimated by the method of least squares, thus providing estimates of the rate of mental rotation. For left-right decisions, the estimated rate was 550 dps for vertically symmetrical letters, 550 dps for horizontally symmetrical letters, and 556 dps for asymmetrical letters. Although slightly above the values typically derived from grouped data, these values are well within the range of individual values (164–800 dps) reported by Cooper and Shepard (1973) for the mental rotation of alphanumeric characters. Top-bottom decisions, by contrast, yielded estimated rates of 2,185, 1,255, and 1,714 dps, respectively, which are well beyond the upper limit of individual variation reported by Cooper and Shepard. Note, however, that the closest estimate to that observed in experiments using the Cooper-Shepard task was that for horizontally symmetrical letters (1,255 dps), again suggesting that subjects occasionally did resort to mental rotation in this case.

Rotation rates for individual subjects. Table 1 shows the mental-rotation rates for each axis of symmetry and each axis of marker for each subject, along with the proportion of variance accounted for by the linear trend representing idealized mental rotation. If we take a somewhat arbitrary proportion of 0.60 as representing a reasonable fit to the data, it can be seen from the table that almost all cases of left-right decisions (22 out of 24) meet this criterion. Of these 22 fits, 15 represent mental-rotation rates within the range of individual variation (164–800 dps) reported by Cooper and Shepard (1973). An additional 3 fits yielded rates between 800 and 1,000 dps. These results confirm that mental rotation was a fairly consistent strategy when left-right decisions were involved.

Top-bottom decisions yielded much more erratic results, with only 9 of the 24 decisions meeting the criterion of

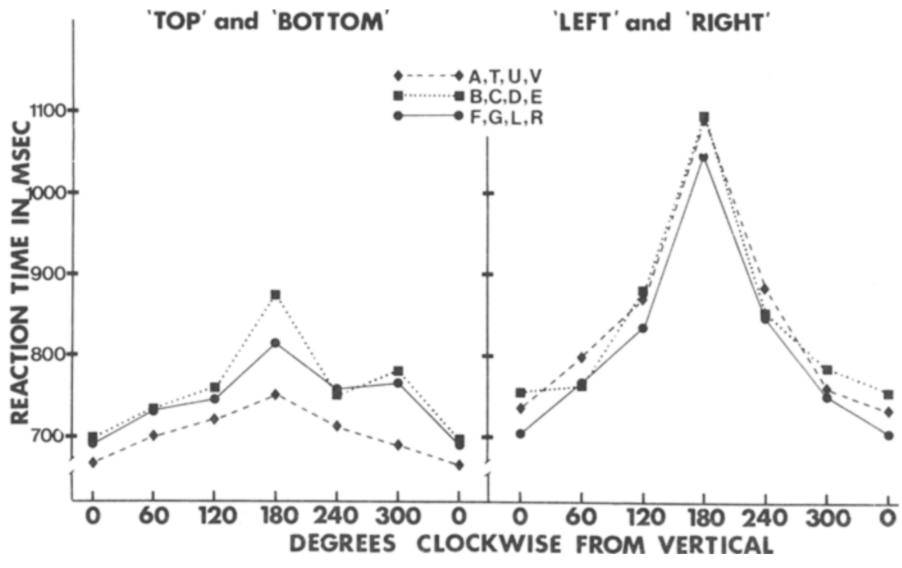

Figure 2. Mean RTs as a function of angular orientation for each axis of marker and each axis of symmetry in Experiment 1.

0.60 of the variance accounted for, and, of those 9, only 2 yielded estimated rates of 800 dps or less. Mental rotation was thus a relatively infrequent strategy in the case of top-bottom decisions.

Rotation rates for individual letters. Although there was little evidence for differences in rate or incidence of mental rotation as a function of the grouping of letters by symmetry, it is conceivable that there were differences within these groupings. In particular, we were concerned that the slight horizontal asymmetry in the letter *B* might have produced a top-bottom cue that may have tended to flatten out the orientation function for top-bottom judgments about the horizontally symmetrical letters. Accordingly, mental-rotation rates were estimated for each letter, for left-right and top-bottom decisions separately. These are shown in Table 2, along with the proportions of variance accounted for by the linear mental-rotation trend.

The results confirm that mental-rotation rate is primarily a function of the axis of the marker and not of the letters themselves. For left-right decisions, the proportion of variance accounted for by the linear mental-rotation function was above 0.60 for all letters, and for all but one (*D*), the estimated rate was below 800 dps. For top-bottom decisions, by contrast, only five of the letters satisfied the criterion of 0.60 of the variance accounted for, and none yielded a rate of less than 800 dps. Rather surprisingly, the letter *B* yielded the closest fit to a mental-rotation function. Far from tending to flatten the function for top-bottom decisions about horizontally symmetrical letters, this letter did most to establish its peaked quality. We conclude that the slight horizontal asymmetry of this letter was unimportant.

The results fail to support the first hypothesis specified in the Introduction; that is, contrary to Rock's (1973) account, subjects do appear to be able to identify the top and bottom of a disoriented character prior to mental rotation, just as they can identify the shape itself without having to mentally rotate it. The results only weakly support the second hypothesis, which is that mental rotation is induced by mirror-image discrimination (Cooper & Shepard, 1973). There was some evidence that top-bottom decisions induced mental rotation more frequently when the letters were horizontally symmetrical and, thus, imposed a mirror-image discrimination, than when the letters were vertically symmetrical or asymmetrical; however, even in the case of horizontal symmetry, the incidence of mental rotation was low relative to that induced by left-right decisions. The incidence of mental rotation in the case of left-right decisions was not discernibly influenced by whether or not the decisions involved mirror-image discrimination.

The data most strongly support the third hypothesis articulated in the Introduction; that is, mental rotation was most strongly induced by left-right decisions, regardless of the symmetry of the letters, and was at best weakly induced by top-bottom decisions. This supports the theory that the primary role of mental rotation in this experiment was to enable the subjects to refer the left and right sides of the letters to the left and right sides of their own bodies (Corballis & Beale, 1983).

Table 1
Proportion of Variance Accounted for and Estimated Rate of Mental Rotation (in Degrees per Second) for Each Subject in Experiment 1

		Axis of Symmetry					
		Vertical		Horizontal		None	
Axis		(*A, T, U, V*)		(*B, C, D, E*)		(*F, G, R, L*)	
of Marker	Subject	Var	Rate	Var	Rate	Var	Rate
Left-Right	1	.88	680	.74	756	.67	1,121
	2	.91	488	.77	444	.85	606
	3	.85	444	.84	417	.88	417
	4	.92	900	.92	1,300	.74	1,041
	5	.82	676	.16	2,136	.80	827
	6	.76	281	.83	297	.73	306
	7	.64	1,224	.52	1,469	.84	892
	8	.75	376	.86	306	.89	345
Top-Bottom	1	.37	5,014	.56	1,850	.03	42,581
	2	.53	1,992	.71	653	.35	1,702
	3	.53	1,920	.41	1,028	.86	870
	4	.49	2,365	.60	1,717	.78	1,556
	5	.53	1,822	.30	1,843	.18	4,662
	6	.89	1,528	.18	1,343	.00	85,052
	7	.37	4,311	.75	1,665	.92	1,702
	8	.56	1,610	.81	1,186	.74	690

Table 2
Proportion of Variance Accounted for and Estimated Rate of Mental Rotation (in Degrees per Second) in Experiment 1

		Axis of Marker			
Axis of		Top-Bottom		Left-Right	
Symmetry	Letter	Var	Rate	Var	Rate
Vertical	*A*	.34	3,976	.74	682
	T	.85	1,299	.87	526
	U	.45	2,629	.79	405
	V	.75	2,253	.96	537
Horizontal	*B*	.88	871	.86	487
	C	.57	952	.64	449
	D	.15	3,000	.65	878
	E	.56	1,549	.90	542
None	*F*	.58	2,619	.77	564
	G	.77	1,568	.82	528
	R	.42	1,222	.82	604
	L	.81	2,025	.91	524

EXPERIMENT 2

The results of Experiment 1 suggested that subjects cannot easily determine which is the left or right side of a disoriented character without first imagining it in its normal upright orientation. The main purpose of Experiment 2 was to find out whether this difficulty lies in discovering the left-right axis itself, or whether the problem is to determine which is the left or right pole of that axis. Evidence reviewed by Rock (1973) suggests that the top-bottom axis is more prominent than the left-right axis in shape recognition; logically, identification of a single axis is sufficient to enable mental rotation to the upright. Consequently, it is conceivable that subjects do not correctly locate the left-right axis until they have mentally rotated the character to the upright. On the other hand, additional evidence suggests that it is the discrimination of left from right that requires reference to egocentric spatial coordinates (Corballis & Beale, 1983), suggesting that it is this discrimination, rather than the identification of the left-right axis, that is the critical factor inducing mental rotation.

In this experiment, therefore, we simply required subjects to make one response if the asterisk was either to the left or to the right of each letter, and another if it was at the top or bottom. We also eliminated the asymmetrical letters, so that the pool of letters was reduced to the four vertically symmetrical ones (*A*, *T*, *U*, and *V*) and the horizontally symmetrical ones (*B*, *C*, *D*, and *E*). To ensure that this alteration was not critical, we also repeated the basic conditions of Experiment 1 with this reduced pool.

As a matter of secondary concern, we also pointed out to half the subjects in Part B of Experiment 2 that certain of the discriminations could be based on distinctive features. In particular, we wanted to determine whether subjects could discriminate the left and right sides of horizontally symmetrical letters without mental rotation, if it was pointed out to them that the two sides of these letters were featurally distinct. Thus, for example, the left side of an *E* is simply a straight line, whereas the right side consists of three end points. Intuitively, one might expect subjects to be able to make use of this information without having to resort to mental rotation.

Method

Subjects. Eight men and 8 women served as subjects; their ages ranged from 21 to 49 years. Four men and 4 women served in each part of the experiment, and within Part B (see below), 2 men and 2 women served in each instruction group.

Apparatus and Stimuli. The apparatus and stimuli were the same as in Experiment 1, except that the letters *F*, *G*, *L*, and *R* were eliminated. The stimulus pool was reduced to the vertically symmetrical letters, *A*, *T*, *U*, and *V*, and the horizontally symmetrical letters, *B*, *C*, *D*, and *E*. Each was presented in six angular orientations, with the asterisk placed to the left, right, top, or bottom, making a total of 192 stimulus cards. Each subject worked twice through the set in random orders, thus receiving 384 trials.

Procedure. The stimuli were presented in the same manner as in Experiment 1.

The 4 men and 4 women who served in Part A were instructed to make one vocal response if the asterisk was either to the left or to the right of each letter, and another if it was either at the top or at the bottom. Half responded "O" in the first case and "X" in the second; for the other half, these labels were reversed.

The remaining subjects served in Part B. The instructions were the same as in Experiment 1—the subjects simply called out "left," "right," "top," or "bottom"—except that 2 of the men and 2 of the women were given specific suggestions as to how they might go about the task. It was pointed out to them that the tops and bottoms of the vertically symmetrical letters were featurally distinct, as were the left and right sides of the horizontally symmetrical letters, and that decisions about these letters might be based upon these distinctive features rather than on mental rotation. All 4 subjects claimed to understand this point. This manipulation was included more in the interests of preliminary inquiry than of serious experiment, which is why the instructed group was so small.

Results and Discussion

Part A. The subjects who were required to identify the axis of each asterisk, but not the pole of that axis, made a total of only 25 errors out of 3,072 trials, an error rate of only 0.81%. There were 12 errors to top-bottom placements and 13 to left-right placements.

RTs for correct responses were subjected to analysis of variance. The independent variables were assignment of labels, axis of symmetry, letter, response (left-right vs. top-bottom), pole (whether the asterisk was left or right, top or bottom), and angular orientation. The effect of angular orientation was significant [$F(5,30) = 8.24$, $p < .001$], but orientation did not interact significantly with response [$F(5,30) = 1.02$] or with axis of symmetry [$F(5,30) = 0.66$]. The triple interaction also was not significant [$F(5,30) = 0.59$]. A linear mental-rotation function fitted to the mean RTs at each orientation accounted for 80% of the variance, but yielded an estimated rotation rate of 3,084 dps. This rate is much too high to be attributed to consistent mental rotation. Figure 3 shows RT plotted against angular orientation for each axis of symmetry and each response.

There was no significant difference between left-right and top-bottom decisions [$F(1,6) = .02$]; the mean RTs were 781 msec and 783 msec, respectively. Hence, there was no evidence that the top-bottom axis was the more salient, as Rock (1973) implied, or that either decision was made in default of the other. Rather, the subjects appeared to be able to determine directly whether a marker was on the left-right or top-bottom axis, without reference to the other axis, and without resorting to mental rotation.

There was a significant effect due to letters [$F(6,36) = 3.87, p < .01$], and a significant interaction between letters and orientations [$F(30,180) = 2.22, p < .01$], although neither effect is significant if one adopts the reduced degrees of freedom (1,6) recommended by Winer (1971) for testing repeated measures effects. RTs were slowest for the letters *U* (849 msec) and *C* (831 msec), probably because subjects tended to confuse these two letters. Linear mental-rotation functions fitted to each letter yielded estimated rates ranging from 1,361 to 6,000 dps, all well beyond the range plausibly attributed to consistent mental rotation. The slowest rate, however, was for the letter *U*, and may reflect an occasional strategy of mental rotation, again perhaps due to the subjects' tendency to confuse this letter with the *C*.

Part B. The purpose of this part of the experiment was twofold: first, to check that the results of Experiment 1 would be sustained with the reduced pool of letters, and second, to investigate whether mental rotation might be influenced by the instructions concerning the use of distinctive features.

Subjects given these instructions made a total of 32 errors in 1,536 trials, an error rate of 2.08%, whereas

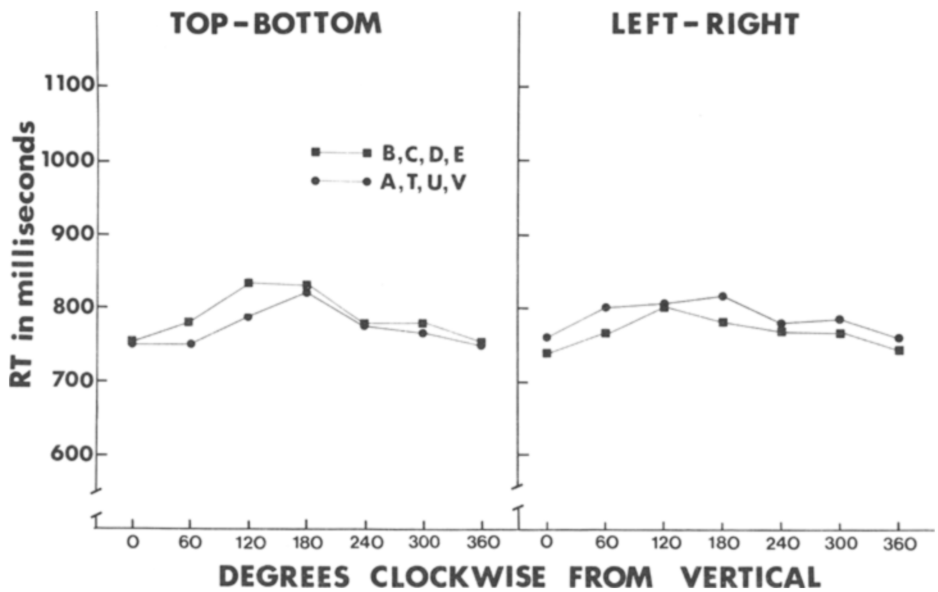

Figure 3. Mean RTs as a function of angular orientation for each axis of marker and each axis of symmetry in Part A of Experiment 2.

the subjects not given the instructions made only 6 errors in 1,536 trials. This difference was significant according to an ANOVA [$F(1,6) = 6.58$, $p < .05$], but must be considered somewhat suspect due to the extreme skewness of the scores. As in Experiment 1, there were more errors for left-right (1.95%) than for top-bottom (0.52%) placements; this difference was not significant [$F(1,6) = 3.33$], but it did interact significantly with groups [$F(1,6) = 6.19$, $p < .05$], with the effect of placement largely confined to the instructed group. We do not attach a great deal of importance to these effects—the noninstructed group seems to have been unusually accurate, and the significant effects may have been due to Type I error.

RTs for correct responses were again subjected to ANOVA. As in Experiment 1, there were significant main effects of angular orientation [$F(5,30) = 19.73$, $p < .001$], axis of marker [$F(1,6) = 7.36$, $p < .05$], and letter [$F(6,36) = 3.68$, $p < .01$]. The interaction between axis of marker and orientation was again significant [$F(5,30) = 10.76$, $p < .001$].

Figure 4 shows that, as in Experiment 1, peaked mental-rotation functions were obtained for "left" and "right" decisions, regardless of the axis of symmetry of the letters. These functions exhibited a greater degree of flattening for orientations close to the upright than did the corresponding functions in Experiment 1; even so, linear mental-rotation functions fitted to the data yielded estimated rates of 613 and 710 dps, accounting for .716 and .775 of the variance for vertically and horizontally symmetrical letters, respectively. The most likely reason for the flattening is that subjects tended not to rotate the letters the full angular distance to the upright, and did not rotate the letters at 60° or 300° at all (Hock & Tromley, 1978). If the 0° points are disregarded, and mental-rotation functions are fitted to the remaining points, the estimated mental-rotation rates reduce to 402 and 482 dps, respectively, which are very close to the estimates typically obtained in studies of the mental rotation of letters. It seems clear that judgments of "left" and "right" again induced the subjects to mentally rotate the letters to some orientation at which it was evident which side was which.

In this experiment, however, the triple interaction between axis of symmetry, axis of marker, and angular orientation was significant [$F(5,30) = 4.38$, $p < .001$]. Although this interaction was not significant in Experiment 1, it represents a trend that was evident in the earlier experiment: As Figure 4 demonstrates, the function for "top" and "bottom" decisions was more peaked when the letters were horizontally symmetrical than when they were vertically symmetrical. A linear mental-rotation function fitted to the data for the horizontally symmetrical letters produced an estimated mental-rotation rate of 894 dps, just beyond the range of individual variation reported by Cooper and Shepard (1973). This suggests that the subjects may have quite frequently resorted to mental rotation when there were no features distinguishing the tops and bottoms of the letters. By contrast, the linear function for the vertically symmetrical letters, although accounting for .723 of the variance, yielded an estimated mental-rotation rate of 2,164 dps.

Table 3 shows the estimated mental-rotation rates and variance accounted for under each combination of instructions, axis of marker, and axis of symmetry. Estimated rates were, in fact, slightly higher for those subjects instructed in the use of critical features, suggesting a slightly reduced incidence of mental rotation. This was especially so in those cases in which distinctive features provided a potential basis for discrimination, namely, in left-right

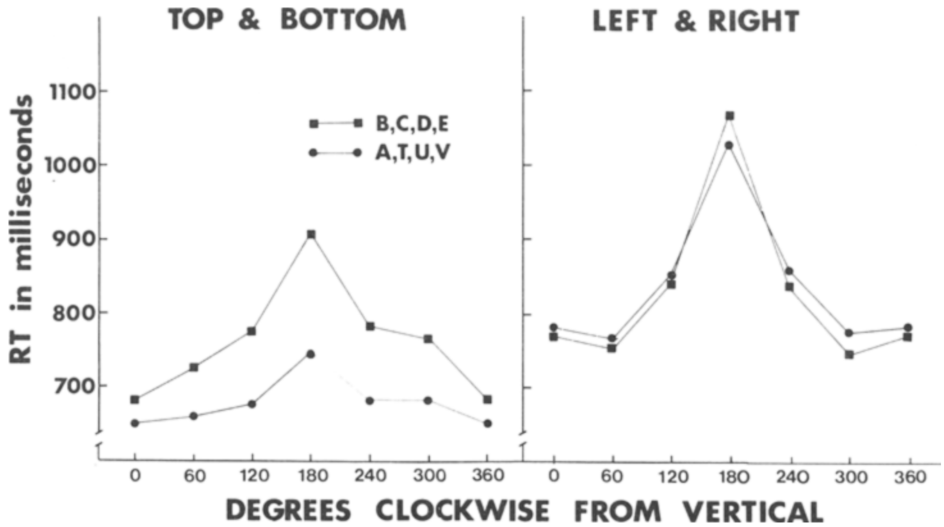

Figure 4. Mean RTs as a function of angular orientation for each axis of marker and each axis of symmetry in Part B of Experiment 2.

decisions about horizontally symmetrical letters (rates of 845 dps for instructed and 611 dps for noninstructed groups), and in top-bottom decisions about vertically symmetrical letters (3,905 dps for instructed, 1,493 dps for noninstructed). However, instructions had no significant effects on the pattern of results; the interactions of instructions with orientation [$F(5,30) = 0.76$], with axis of marker and orientation [$F(5,30) = 0.35$], and with axis of marker, orientation, and axis of symmetry [$F(5,30) = 0.41$], all proved trivially small. These null results may be due in part to the small sample sizes and consequent lack of statistical power, however, and should not be taken as definitive.

The results of Part B essentially confirm those of Experiment 1, except that there was somewhat more evidence for mental rotation in decisions about the top and bottom of horizontally symmetrical letters—decisions that require mirror-image discrimination. This evidence was more marked for the group that was not instructed in the use of critical features. Overall, however, instructions had, at most, only a very slight influence on the pattern of results.

EXPERIMENT 3

In this experiment, we examine the possibility that the results of the first two experiments were influenced by the fact that the stimuli, letters, were highly familiar. Consequently, the letters were replaced by symbols which were unfamiliar to the subjects, but which were of a complexity approximately equal to that of letters. The symbols were presented as vertically symmetrical in their canonical or upright orientations under some conditions and as horizontally symmetrical under others, thus permitting a measure of control that is not possible with letters. We did not use asymmetrical symbols.

Method

Subjects. Four men and 4 women volunteered. Their ages ranged from 17 to 37 years. All were right-handed.

Apparatus and Stimuli. Four nonverbal shapes were selected from among the architectural symbols printed on Letraset Sheet No. AS630. None of the subjects was familiar with any of the symbols prior to the experiment. Each symbol was symmetrical about one axis, and was assigned a normal upright orientation that differed for each of four groups of subjects. Hence, the normal upright of each symbol was vertically symmetrical for two of the groups and horizontally symmetrical for the other two. The assignment of the upright orientations of each symbol to each group is shown in Figure 5. As in the first two experiments, an asterisk marker was placed to the top, bottom, left, or right of each symbol, and the symbols were presented in the same six angular orientations. There were 96 stimulus cards in all.

Procedure. The subjects were shown the symbols 15 min before the start of the session and asked to memorize them in their designated upright orientations. The task was explained to them, and after they thought they had become reasonably familiar with the symbols, they were invited to practice by simply looking at the stimulus cards, making a decision, and then checking their answers against the correct answers, which were written on the backs of the cards.

The cards were then presented in random order in the tachistoscope. From this point, the procedure was the same as in Experiment 1, that is, the subject was to say as quickly and accurately as possible whether each asterisk was to the "left," "right," "top,"

Table 3
Proportion of Variance Accounted for and Estimated Rate of Mental Rotation (in Degrees per Second), Part B of Experiment 2

Group	Axis of Symmetry	Top-Bottom Var	Top-Bottom Rate	Left-Right Var	Left-Right Rate
Instructed	Vertical	.69	3,905	.72	705
	Horizontal	.72	1,124	.69	845
Not Instructed	Vertical	.70	1,493	.71	545
	Horizontal	.94	740	.81	611

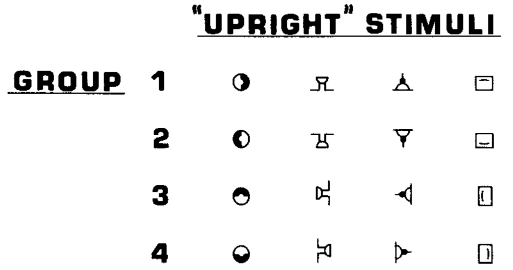

Figure 5. Symbols used in Experiment 3, as allocated in "upright" orientations to each group of subjects.

or "bottom" of each symbol with respect to its normal upright orientation. Each subject worked through the 96 stimulus cards three times, in separate sessions.

Results and Discussion

The subjects made a total of 45 errors, or 3.91%, when the asterisk was to the left or right, and 32 errors, or 2.78%, when it was to the top or bottom. This difference was not significant [$t(7) = 1.17$].

ANOVA was performed on the RTs for correct responses. There were significant main effects due to angular orientation [$F(5,20) = 11.71$, $p < .001$] and to session [$F(2,8) = 25.46$, $p < .001$]. There was no significant main effect of axis of marker [$F(1,4) = 0.82$], as there had been in Experiments 1 and 2B.

In this experiment, moreover, the interaction between angular orientation and axis of marker was not significant [$F(5,20) = 0.72$], indicating that the incidence of mental rotation was not simply a matter of whether left-right or top-bottom decisions were required, as was the case in Experiment 1. There was, however, a significant triple interaction between angular orientation, axis of marker, and axis of symmetry [$F(5,20) = 6.53$, $p < .001$], and this is plotted in Figure 6.

This interaction suggests that mental rotation was generally confined to those decisions requiring mirror-image discrimination, as proposed by Cooper and Shepard (1973). Thus, the most peaked functions were those for top and bottom decisions about horizontally symmetrical symbols and for left and right decisions about vertically symmetrical symbols. As in the first two experiments, linear-mental-rotation functions were fitted to the four curves. For top and bottom decisions, this yielded an estimated rate of mental rotation of 467 dps and accounted for .85 of the variance when the symbols were horizontally symmetrical, suggesting a high incidence of mental rotation. When the symbols were vertically symmetrical, by contrast, the estimated rate was 1,864 dps and the proportion of variance accounted for was only .31. In this case, it seems likely that the subjects relied principally on critical features in making their decisions. For left and right decisions, the distinction between mirror-image and non-mirror-image discriminations was not quite so clear-cut, but it was in the same direction. For vertically symmetrical symbols, requiring a mirror-image discrimination, the estimated mental-rotation rate was 793 dps, and for horizontally symmetrical symbols, whose left and right sides could be distinguished in terms of critical features, the estimated rate was 1,050 dps. However, the linear-mental-rotation function provided the better fit in the latter case, accounting for .89 of the variance compared with only .79 for the vertically symmetrical symbols. This was

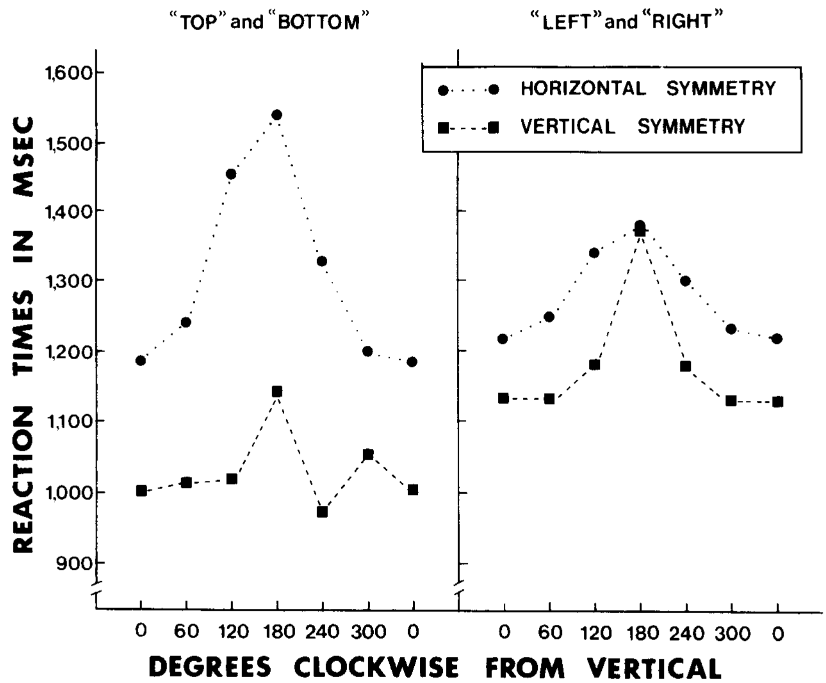

Figure 6. Mean RTs as a function of angular orientation for each axis of marker and each axis of symmetry in Experiment 3.

due, in part, to the flattening of the function for orientations close to the upright in the case of the vertically symmetrical symbols—the mean RTs at orientations of 0°, 60°, and 300° were within 1 msec of each other. As already noted, this flattening is commonly observed in studies of mental rotation, and is taken to mean that subjects do not always rotate the stimuli the full angular distance to the upright (Cooper & Shepard, 1973; Hock & Tromley, 1978). If the RT for 0° is ignored and the mental rotation rate is estimated from the remaining points, the estimate for vertically symmetrical symbols reduces from 793 to 536 dps.

We conclude that mental rotation, in this experiment, was induced primarily by the requirement to make mirror-image discriminations, in accordance with the second hypothesis articulated in the Introduction. Although mirror-image discrimination requires the ability to distinguish left from right (Corballis & Beale, 1976), it does not necessarily require the use of the labels "left" and "right"; thus, the most compelling evidence for mental rotation in this experiment was actually obtained when top-bottom decisions were required. As in all three experiments, however, the mirror-image component was less evident in left-right than in top-bottom decisions, suggesting that left-right labeling also exerted an influence.

GENERAL DISCUSSION

Taken together, the results of all three experiments show that decisions about the axes of disoriented shapes sometimes induce mental rotation and sometimes do not, depending to some extent on the task and the stimuli. The fact that mental rotation did not occur under all conditions confirms earlier evidence that mental rotation is not a necessary component of the actual recognition of a disoriented shape, at least if one defines mental rotation in terms of the peaked orientation function first demonstrated by Cooper and Shepard (1973). We, therefore, reject the first hypothesis articulated in the Introduction.

From Experiment 2A, moreover, we conclude that mental rotation is seldom, if ever, involved in identifying the axes themselves, at least in the case of highly familiar shapes, such as letters. The fact that the axes are not defined until the shapes are identified further reinforces the conclusion that identifying familiar shapes does not require mental rotation. The role of mental rotation seems, therefore, to be restricted to decisions involving the poles of the axes, although not all such decisions require mental rotation.

In the present experiments, there seemed to be two task ingredients that tended to induce mental rotation, although neither did so under all conditions. The stronger of the two corresponds to the third hypothesis described in the Introduction: that mental-rotation functions were most evident when subjects were required to identify the left or right sides of the shapes. Presumably, this is because the labels "left" and "right" are egocentrically defined (Corballis & Beale, 1976), so that the sides of a shape must be referred to our own bodies if they are to be distinguished. In the case of letters, this was so even when they contained distinct features on their left and right sides. In the case of relatively unfamiliar symbols (Experiment 3), however, the subjects were evidently able to make some use of the features distinguishing the left and right sides of the horizontally symmetrical symbols, since mental rotation was less evident than in the case of vertically symmetrical symbols. We suspect that people may learn letters without explicit reference to the features marking the letters' left and right sides (many of them have no such features), whereas the subjects in Experiment 3, in view of the nature of the task they were to perform, may have paid special heed to any features distinguishing the poles of the axes.

The second and weaker task ingredient underlying mental rotation corresponds to the second hypothesis stated in the Introduction: mirror-image discrimination. This factor was more marked in top-bottom than in left-right decisions, which tended to induce mental rotation whether or not mirror-image discrimination was involved. Thus, in all three experiments, mental rotation was a more common strategy in top-bottom decisions when the stimuli were horizontally symmetrical than when they were vertically symmetrical, presumably because the vertically symmetrical shapes provided a featural basis for the discrimination. This effect was especially marked in Experiment 3, perhaps because the subjects paid special heed to distinctive features in learning the symbols. These data add to Corballis and McLaren's (1984) demonstration that mental rotation may be induced by the discrimination of disoriented shapes whose canonical (or upright) forms are up-down mirror images.

Mental rotation may have been somewhat restricted in the case of top-bottom mirror-image discriminations by a difficulty inherent in the act of mental rotation itself. In this case, the observer must find the upright orientation by aligning the left-right axis of the shape with the left-right axis of space. Because of the special nature of left and right (Corballis & Beale, 1976), this may be more difficult than the act of aligning the top-bottom axis of a shape with that of space, as required for left-right discriminations about vertically symmetrical shapes. This might explain why RTs were exceptionally long for top-bottom mirror-image discriminations in Experiment 3; Corballis and McLaren (1984) found similarly that up-down mirror-image discriminations took longer than left-right ones, although both evidently required mental rotation. The difficulty of rotating a horizontally symmetrical shape to the upright might also explain why mental rotation was a relatively infrequent strategy in the case of top-bottom decisions about horizontally symmetrical letters (Experiments 1 and 2), although the observer can avoid mental rotation only if there is information in the unrotated image as to which is top or bottom. Such information may be available only in highly familiar shapes; its possible nature is discussed in the next section.

Aside from the study by Corballis and McLaren (1984), previous studies of the mental rotation of singly presented shapes have been restricted to the discrimination of left-right mirror images, and have tended to give a more consistent pattern of mental rotation than was evident in the present study. Perhaps this is because both of the ingredients identified in this paper have been involved in these earlier studies. Discrimination of a forward from a backward letter, for instance, implicitly requires an identification of which side is which, so that the sides can be matched against those of a stored representation. At the same time, this discrimination is a mirror-image discrimination. That is, mental rotation is likely to be most consistent in the case of left-right mirror-image discrimination. These two ingredients were teased apart in the present experiments, thus weakening the inducement to a mental-rotation strategy. It might also be noted that in the study by Corballis and McLaren (1984), the orientation functions were not so sharply peaked when the discriminations required were between up-down mirror images as when they were between left-right mirror images, again suggesting that the left-right and mirror-image aspects of the task have separate and cumulative effects on the incidence of mental rotation.

Toward a Theory of Recognition of Disoriented Shapes

We now sketch a theory as to how people might recognize disoriented shapes. We suggest that when a shape is presented, the perceiver first extracts a representation that is independent of both orientation and parity. Such a representation might consist, for instance, of a distribution of distances between all possible pairs of points on the contours of the shape (Deutsch, 1955). The representation is supplemented, however, by descriptors representing the parity of the shape (i.e., which of two mirror-image forms it is) and the angular orientation of the shape in phenomenal space.

This representation is then compared, probably in parallel (see Ratcliff, 1978), with stored representations of known shapes. Each stored representation also consists of descriptors that are independent of orientation and parity, but with additional descriptors representing the normal upright and normal parity. If the presented shape is disoriented or mirror reversed, then the orientation and parity descriptors will not match the corresponding descriptors in the appropriate stored representation. For most common objects and shapes, however, the orientation- and parity-free descriptors will be sufficient to ensure correct recognition. Hence, for example, recognition of rotated letters is normally sure and rapid, although not quite as rapid as that of upright letters (Jolicoeur & Landau, 1984). Contrary to Rock (1973), therefore, we conclude that recognition is normally accomplished independently of the establishment of orientation.

There are exceptions. In some type fonts a lowercase *d* is indistinguishable from a *p*, or an uppercase *M* from a *W*, unless orientation is specified. If any of these letters is laid on its side, the specification of orientation may be quite arbitrary. Similarly, Rock's (1973) example of a tilted square, which may be perceived either as a square or as a diamond, but not simultaneously as both, seems to be a special case rather than an example of a general rule; the orientation descriptor is necessary in order to specify which of the two shapes it is.

Once a disoriented shape is recognized, its orientation may then be specified (provided it was not already involved in the recognition process itself). Part A of Experiment 2 showed that subjects can rapidly perceive the top-bottom and left-right axes of a disoriented letter, and that this does not normally require mental rotation. Logically, specification of these axes cannot occur until recognition has been accomplished, since information about the upright orientation is available only in the stored representation. To distinguish the poles of these axes *may* require mental rotation, however. Featural elements may be sufficient to discriminate the poles, especially in the case of the top versus the bottom of a shape. They do not seem to be sufficient to establish which is the left or right side, however, at least in the case of letters. We have suggested that this may be due to the special nature of the labels "left" and "right," which are essentially defined in terms of the sides of the body; to discriminate the left and right sides of a disoriented letter, therefore, requires mental rotation of the letter to the upright so that its sides can be directly related to the sides of the body. However, in Experiment 3, the subjects evidently were able to make use of featural cues to distinguish the left and right sides of relatively unfamiliar architectural symbols without mental rotation, at least some of the time. We suspect that this may have been due to a strategy of associating verbal labels with the sides of the symbols when specific features distinguishing the sides were available.

In terms of our conceptualization, the act of mental rotation is that of aligning the orientation descriptor of the extracted representation with that of the stored one. It may be necessary to do this if the orientation-free descriptions contain no information that enables discrimination of the poles of the axes, and the task is to identify these poles. One would expect featural differences between the poles to be incorporated in the orientation-free descriptions, so that mental rotation is less likely to be necessary where such featural markers exist. What is somewhat surprising, however, is that the subjects in Experiments 1 and 2 were often apparently able to discriminate the tops and bottoms of horizontally symmetrical shapes without mental rotation, despite the fact that featural markers are not available. It is difficult to conceptualize an orientation-free description of a horizontally symmetrical shape that characterizes its top as distinct from its bottom.

A similar difficulty arises with respect to the representation of parity. Although subjects typically mentally rotate alphanumeric characters in order to determine whether they are normal or mirror reversed, they nevertheless identify normal characters more rapidly than mirrored ones regardless of orientation, and do so in the absence of mental rotation (Corballis et al., 1978; Corballis & Nagourney, 1978). Again, it is difficult to conceptualize an orientation-free description of a shape that is not also parity-free. Indeed, parity can be regarded as an aspect of orientation, since mirror reversal can be regarded as the turning over of a shape in (n+1)-space, where the shape itself is represented in n-space. A forward two-dimensional letter, for instance, can be mirrored by turning it over in the third dimension, just as a left-hand glove can, in principle, be converted to a right-hand glove by turning it over in the fourth dimension.

We suspect that the parity effect in the recognition of disoriented alphanumeric characters arises, not from the nature of the orientation-free representation, but because there are direct representations of normal characters in varying orientations; that is, we do have some experience of inverted *normal* letters and digits, but virtually no experience of inverted *backward* letters and digits. These representations may be too weak to permit an accurate judgment as to whether an actual disoriented character is normal or backward, but strong enough to give an advantage to normal characters in a recognition task. Similarly, knowledge of which is the top or bottom of a disoriented character may derive in part from a direct knowledge of what disoriented characters look like, so that mental rotation is not always necessary to decide between top and bottom, even when there are no distinguishing features. However, direct representations of disoriented shapes are presumably rather weak, and are available, we suspect, only for highly familiar shapes. This could be why there was no evidence from Experiment 3 that subjects could tell the tops from the bottoms of horizontally symmetrical architectural symbols without mentally rotating them to the upright.

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